Solar Wind Turbulence, Diffusion Coefficients, and Cosmic Ray Modulation

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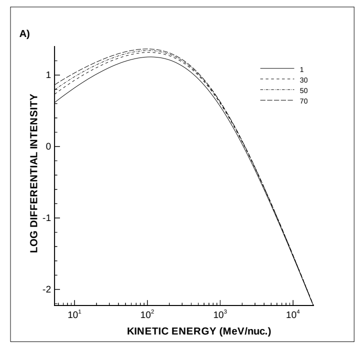
Abstract

A newly developed model for describing the radial evolution of low frequency turbulence in the solar wind is used to model the cosmic ray spatial diffusion tensor in the heliosphere and hence galactic cosmic ray modulation.

1 Introduction:

To understand the heliospheric dependence of the cosmic ray diffusion tensor requires both a fundamental understanding of the structure of the diffusion coefficients themselves and the heliographic properties of the underlying low frequency turbulence responsible for scattering the cosmic rays. The formal structure of the diffusion tensor now appears to be well understood. A model describing the heliocentric evolution of the power in magnetic fluctuations δB^2 and associated correlation lengths has achieved notable success in accounting for the observed decay in δB^2 with radial distance, the evolving correlation length with radial distance, and the dissipative heating of the solar wind [Zank et al., 1996; Matthaeus et al., 1999]. These elements were combined by Zank et al. [1998] to determine the radial and latitudinal dependence of the cosmic ray diffusion tensor throughout the heliosphere. In combining the functional form of the cosmic ray spatial diffusion tensor and a model for the radial evolution of low frequency turbulence, Zank et al. [1998] had to address (1) the role of sources of turbulence in the solar wind in determining radial cosmic ray mean free paths, and (2) the detailed form of the perpendicular and drift expressions of the diffusion tensor.



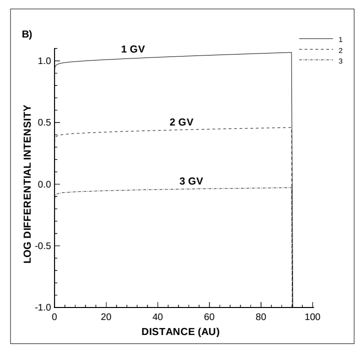


Figure 1: Differential proton intensities as a function of (A) kinetic energy at heliocentric distances of 1, 30, 50, and 70 AU, and (B) radial distance for 1, 2, and 3 GV particle energies. This corresponds to a decaying turbulence model.

Three principle sources exist for turbulence in the outer heliosphere. The first is shear associated with the interaction of fast and slow speed streams (Coleman 1968) and the second is compressional effects associated with both stream-stream interactions and shock waves. The third source, which occurs beyond the ionization cavity, is turbulence generated by the ionization of interstellar hydrogen. Both the shear and compressional source terms can be expressed as (Zank et al. 1996) $\dot{E}_{shear(comp)} = C_{shear(comp)}(u/r)E_b$, where E_b is the fluctuation energy density, u is the solar wind speed, and $C_{shear(comp)}$ is a prescribed constant.

The ionization of interstellar neutral H introduces an unstable ring-beam distribution of pickup ions into the solar wind. The pickup ions are assumed to scatter in pitch-angle by excited and ambient low-frequency waves while preserving their energy in the wave frame. If the pickup ion generated (unstable) parallel propagating modes dominate the fluctuation spectrum, then the pickup ions scatter onto a "bispherical" shell distribution, whereas elastic scattering in the solar wind frame would yield a spherical distribution. The difference in kinetic energy between the spherical and bispherical distributions is given to the waves and their free energy is $\sim V_A/u$ of the initial pickup ion number density (Williams & Zank 1994). The source term for pickup ion generated turbulence is (Williams & Zank 1994)

$$\dot{E}_{PI} = \frac{\mathrm{d}n_{PI}}{\mathrm{d}t}\frac{V_A U}{n_{SW}} = \frac{U V_A n_H^{\infty}}{n_{SW}^{o}\tau_{ion}^{o}} \exp\left[-\lambda_{PI}\theta/r\sin\theta\right], \tag{1}$$

where $n_{PI,SW}$ denote pickup ion and solar wind number densities respectively and the time derivative refers to a creation rate rather than a convective derivative. We express the pickup ion creation rate in terms of the cold gas interstellar neutral distribution approximation and n_H^{∞} should be interpreted as the neutral number density at the termination shock. This approximation is reasonable provided n_H^{∞} is chosen properly. Finally, τ_{ion}^{0} is the neutral ionization time at 1 AU, λ_{PI} the ionization cavity length scale, and θ the angle between the observation point and the upstream direction.

We shall explore the implications of the different sources of turbulence on both the modulated galactic cosmic ray spectrum and on the spatial gradients of cosmic rays of different energies.

Turbulence in the ecliptic plane appears to be a combination of slab and 2D turbulence, with the latter dominant [Zank and Matthaeus, 1992; Bieber et al., 1994]. For cosmic rays resonant with the MHD turbulence in both the inertial and energy ranges, the 2D component is effectively invisible. The cosmic ray mean free path is well approximated by [Zank et al., 1998]

$$\lambda_{\parallel} = \frac{3\kappa_{\parallel}}{v} = 3.1371\frac{B^{5/3}}{\delta B_{x,slab}^2}\left(\frac{P}{c}\right)^{1/3}\ell_{slab}^{2/3}\left\{1+\frac{7/9A}{(q+1/3)(q+7/3)}\right\}, \tag{2}$$

$$A = (1+s^2)^{5/6}-1; \qquad s \equiv 0.746834 R_L/\ell_{slab}; \qquad q = \frac{5s^2/3}{1+s^2-(1+s^2)^{1/6}}, \tag{3}$$

where R_L is the particle Larmor radius, B the interplanetary magnetic field, $\delta B_{x,slab}^2$ the variance of the x component of slab geometry fluctuations, and $P \equiv pc/Ze$ the particle rigidity (p momentum, c the speed of light, and Ze particle charge), and ℓ_{slab} is the correlation length for slab turbulence. Although an approximation, expression (2) is in very close accord with the exact Fokker-Planck result. The fractional term in braces is of particular importance in the outer heliosphere when the particle Larmor radius can become comparable to or greater than the correlation length ℓ_{slab}. In this case, the ion no longer scatters resonantly with turbulent MHD fluctuations in the inertial range but rather with fluctuations that reside in the much flatter energy-containing range. As a result, depending on how the correlation length evolves with heliocentric distance, the scaling of $\lambda_{\parallel}$ with respect to both rigidity P and correlation length can change from inner to outer heliosphere.

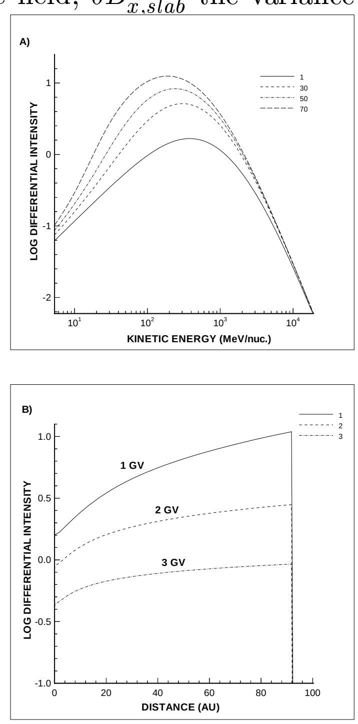


Figure 2: Pickup ion driven turbulence model.

The perpendicular mean free path is given by $\lambda_{\perp} = 3\kappa_{\perp}/v = R_L\Omega\tau/\left(1+(\Omega\tau)^2\right)$ where, τ is a "scattering/relaxation time", and Ω the particle gyrofrequency. Bieber and Matthaeus [1997] suggest that $\Omega\tau = \frac{2}{3}R_L/D$, where D denotes a magnetic field line diffusion coefficient. Zank et al. [1998] modelled D by (1) a modified quasi-linear theory (QLT) for which $D \equiv D_{QLT} = (\delta B^2/2B^2)\ell_{slab}$ [Jokipii, 1966; Forman et al., 1974], or (2) by a non-perturbative approach to the diffusion of magnetic fields in slab or 2D turbulence [Gray et al., 1996], for which $2D \equiv 2D_{\perp} = D_{slab} + \sqrt{D_{slab}^2 + 4D_{2D}^2}$ ($D_{slab} = D_{QLT}$, $D_{2D} = (\delta B/B)\tilde{\ell}$).

The non-perturbative model is further distinguished by the choice of the mesoscale correlation length $\tilde{\ell}$, which we assume to be either $\tilde{\ell} = \ell_{slab}$ (NP1) or $\tilde{\ell} = 10^2 \ell_{slab}$ (NP2).

We therefore have three distinct sources of turbulence in the solar wind and three possible forms of the perpendicular diffusion coefficient. Results are presented here which demonstrate how cosmic ray modulation models are effected by each of these elements. Since space is limited, we present results for the NP2 model only and for four cases: no driving of the turbulence i.e., a purely decaying turbulence model; the driving of turbulence by stream-shear and compressible effects; turbulence driving by pickup ions only, and finally, turbulence driving by stream-shear, compression, and pickup ions. The results illustrate one facet of our systematic study of cosmic ray modulation by turbulence in the heliosphere.

2 Results and discussion

The spherically symmetric cosmic ray transport equation

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 u\right)\frac{p}{3}\frac{\partial f}{\partial p} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \kappa_{rr}\frac{\partial f}{\partial r}\right) + Q, \quad (4)$$

is solved, where $f(r, p, t)$ is the isotropic part of the distribution function for cosmic rays with momentum p at time t and distrance r from the Sun. The radial spatial diffusion coeeficient is $\kappa_{rr} = \kappa_{||} \cos^2 \Psi + \kappa_{\perp} \sin^2 \Psi$, u is the solar wind speed, Q is a source, and Ψ the familiar IMF angle. The spatial diffusion coefficient is computed using the δB^2 and correlation length transport equations of Zank et al. [1996]. The ecliptic parameters are listed in Table 1 of Zank et al. [1998].

To solve (4), we use the approach of Steenkamp [1995] which solves for $f(r, p, t)$ on a pre-defined (r, p)-grid. The source Q is assumed to be zero and the solar wind speed u is held constant over the entire spatial domain. The simulations are initialized using a galactic cosmic ray spectrum $\propto (v/R^2c)\,(T + 0.5E_0)^{-2.6}$ (T the kinetic energy of the proton, and E_0 the rest mass energy of a proton). A steady-state solution is then calculated. Throughout the simulations, the outer radial boundary is held constant at the assumed galactic spectrum.

Figures 1A-4A show the differential cosmic ray intensity ($p^2 f$) of protons as a function of kinetic energy per nucleon, calculated for the four turbulence driving models described above. We restrict our perpendicular diffusion model to the NP2 case [Zank et al., 1998]. Figures 1B-4B show the radial gradient of the cosmic ray intensity for 1, 2, and 3 GV protons. All cases were restricted to the ecliptic plane.

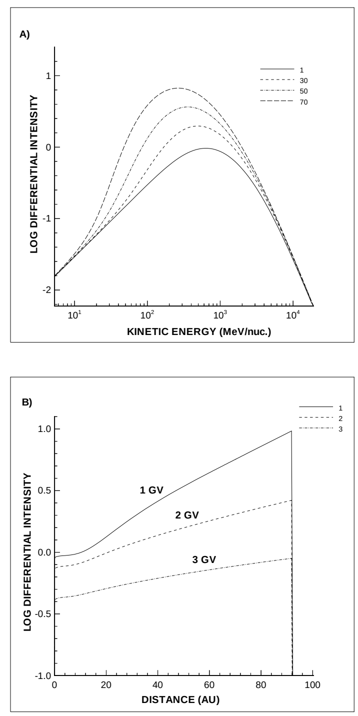


Figure 3: As in Figure 1 but for a shear driven turbulence model.

In the absence of turbulence source terms in the heliosphere i.e., assuming decaying turbulence only, the modulated spectrum (Figure 1A) is virtually unchanged at all heliocentric radii. This is illustrated more clearly in Figure 1B where the cosmic ray gradient is virtually flat with increasing distance. Figure 2 corresponds to turbulence driving by steam-shear only. Since the source term for shear driving [equation (2)] has an r^{-1} dependence, its importance is limited to within ~ 10 AU. Thereafter, the turbulence decays. Thus, low energy protons are modulated more than in the Figure 1 case and the radial cosmic ray gradient is steep initially, after which it flattens (corresponding to the decaying turbulence phase). In the absence of shear with pickup ion driving only, the situation is reversed with most modulation occuring in the outer heliosphere. The radial cosmic ray gradient (Figure 3B) is flat initially (decaying turbulence) after which it steepens strongly (driving by pickup ion turbulence beyond the ionization cavity). The modulated spectra (Figure 3A) are reduced significantly in amplitude compared to the shear driving example. Finally, Figure 4 corresonds to driving by both shear and pickup ions and obviously combines features of both.

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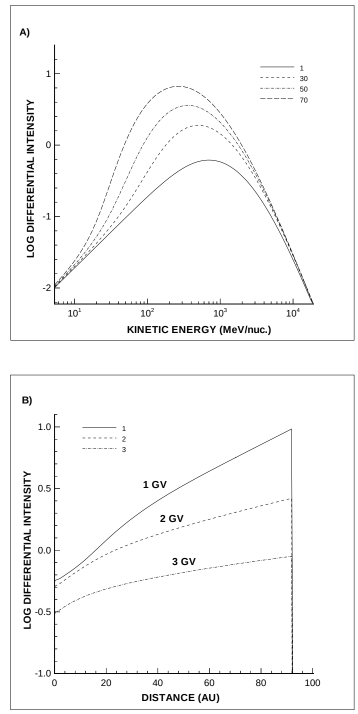

Figure 4: Fully driven turbulence model.